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PITTSBURGH, PENNSYLVANIA 15213

DEPARTMENT OF
MECHANICAL ENGINEERING

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WEAR MECHANISMS
FOR METALLIC SURFACES
IN SLIDING CONTACT

Second Annual Report

September 1975 - October 1976

Sponsored by the
Office of Naval Research
under
Contract No. N00014-67-A-0314-0025
NR 097-396

R. KOMANDURI
M. C. SHAW

Processing Research Institute
Carnegie-Mellon University
Pittsburgh, Pennsylvania 15213

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(1) Spherical metal particles in the size range of 1/2 to 60 μ found when grinding chips are examined in the scanning electron microscope and a mechanism for their formation based on surface energy is presented.

(2) Micron-sized spherical particles in sliding contact are found to reduce the static coefficient of friction, as with the case of larger-sized balls and rollers in bearings.

(3) A mechanism for the accelerated wear of bearing surfaces due to the cutting action of the spherical particles between bearing surfaces in sliding

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20. contact is proposed and verified experimentally.

(4) A potential method for reducing galling wear of materials at high speed sliding contact is presented using a newly developed alloy design that involves the atomization of the liquid alloy in an inert atmosphere and the consolidation of the resulting powder by sintering hydrostatically compressed billets. This results in a more uniform distribution of small sized carbides throughout the matrix as compared to nonuniform distribution of large sized carbides in the wrought material. Segregation of carbides can result in large areas of softer matrix which are potential regions for adhesion and consequent galling.

ABSTRACT

1. Spherical metal particles in the size range of 1/2 to 60 μ found when grinding chips are examined in the scanning electron microscope and a mechanism for their formation based on surface energy is presented.

2. Micron-sized spherical particles in sliding contact are found to reduce the static coefficient of friction, as with the case of larger-sized balls and rollers in bearings.

3. A mechanism for the accelerated wear of bearing surfaces due to the cutting action of the spherical particles between bearing surfaces in sliding contact is proposed and verified experimentally.

4. A potential method for reducing galling wear of materials at high speed sliding contact is presented using a newly developed alloy design that involves the atomization of the liquid alloy in an inert atmosphere and the consolidation of the resulting powder by sintering hydrostatically compressed billets. This results in a more uniform distribution of small sized carbides throughout the matrix as compared to nonuniform distribution of large sized carbides in the wrought material. Segregation of carbides can result in large areas of softer matrix which are potential rggions for adhesion and consequent galling.

ACKNOWLEDGEMENTS

This work was sponsored by a grant from the Office of Naval Research under Contract Number N00014-67-A-0314-0025, NR 097-396.

The authors wish to thank Lt. R. S. Miller and Dr. K. E. Ellingsworth for many interesting discussions and valuable suggestions.

The tool steels used in the study of sphere formation and in galling wear were generously provided by the local Crusible Materials Research Center, Colt Industries. The authors would like to thank Drs. E. J. Dulis and T. Neumeyer of Crusible Research for their interest in this work.

Some of the tests have been conducted by Mr. S. Lakshmipathy, a Research Assistant of Mechanical Engineering Department and the authors acknowledge his contribution.

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I. FORMATION AND ROLE OF SPHERICAL PARTICLES

Although spherical particles have been observed in grinding debris for a long time [1], it is only since 1970 when Scott and Mills [2] first reported the observation of spherical wear particles on the surface of fatigue cracks formed on ball bearings that had been subjected to rolling contact fatigue that interest has grown as to its mechanism of formation and the implication of accelerated wear once the spherical particles have been formed.

Stowers and Robinowicz [3] observed spherical wear particles in their fretting corrosion studies in which silver oscillates on silver at low frequency in the absence of a lubricant. They observed both cylindrical and spherical particles and suggested that these particles may roll between the sliding surfaces and reduce the coefficient of friction in a manner similar to ball and roller bearings. In a recent paper, Komanduri et al.[4] established Stowers and Rabinowicz's hypothesis experimentally that the micron-sized particles in sliding contact do in fact reduce the static coefficient of friction as with large-sized ball and roller bearings. Based on this, it appears that the presence of spherical particles between bearing surfaces in sliding contact may in fact be advantageous since they may reduce friction as in the case of the static friction results.

Middleton et al. [5] found spherical wear particles in jet engine lubricating oil and found their number to increase with bearing deterioration. Seifert and Westcott [6] used a magnetic device that separates metallic wear particles from oil to produce a spectrum of particle sizes in what is referred

to as a ferrogram. Based on the above work, Scott and Mills [7] proposed that the increase in the number of spherical particles present in an oil sample be considered as a potentially useful diagnostic tool for detecting the failure of high speed ball bearings. This implies that wear progresses at an accelerating rate owing to the presence of the spherical particles between bearing surfaces in sliding contact and contradicts the static experimental results of lower friction coefficient and consequently lower wear. Further, altough Scott and Mills proposed that the presence of an increasing number of spherical particles in the lubricating oil be used as a tool for detecting the failure of bearing surfaces, no mechanism was proposed to explain this accelerated wear resulting from the presence of these spherical particles in between the bearing surfaces in sliding sontact. In this report a mechanism for this accelerated wear of bearing surfaces, due to cutting action by the spherical particles between bearing surfaces in sliding contact, is proposed and verified experimentally.

Although the static friction experiments with spherical particles gave lower friction coefficients, as with large-sized balls and rollers in a bearing, the experiments under dynamic conditions gave higher wear and a higher coefficient of friction with spherical particles than without. A explanation for this difference in the static and dynamic test results is based on the fact that the spherical particles are free to move over large distances with large mechanical interaction (considerable depth of cut) unlike in ball and roller bearings, resulting in chip formation, subsurface plastic deformation and higher wear.

In this chapter different aspects of spherical particles (mechanism of their formation, potential role as friction reducers and a mechanism for the accelerated wear by these particles due to cutting action) are presented in the following three publications.

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1. M. C. Shaw, "Metal Cutting Principles," MIT Press, Massachusetts, 1953.
2. D. Scott and G.H. Mills, Wear 16 (1970) p. 236.
3. I. F. Stowers and E. Rabinowicz, J. Appl. Phys., 43, (1972) p.2485.
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II. INVESTIGATION ON A POTENTIAL METHOD OF REDUCING GALLING WEAR

INTRODUCTION

In our first annual report [1] we have discussed the mechanism of galling at high speed sliding. In this report we present a potential method for reducing galling wear of materials in sliding contact. The approach is based on newly developed alloy design that involves atomization of the liquid alloy in an inert atmosphere and the consolidation of the resulting powder by sintering hydrostatically compressed billets [2]. The net result is a more uniform distribution of small sized carbides throughout the matrix as compared to the wrought material. The potential advantages of such a uniform distribution of small second phase particles in reducing galling wear, are as follows:

1. Lesser tendency for adhesive wear
2. Lesser tendency for abrasive wear

These will be discussed shortly.

It is well known that galling is initiated by repeated adhesion and transfer of material between two mating members in sliding contact. In order to control galling, wear by adhesion has to be minimized. The familiar approach is to strengthen the matrix by dispersion and/or solid solution alloying or by use of hard second phase particles generally in the form of cubic carbides. The new concept for reducing galling, involves the use of controlled size and distribution of carbides in the matrix achievable by the new steel making process outlined above without altering the chemical composition.

Large size carbides (several microns) when protruding from the matrix can produce micron sized lathe chip type wear debris which can be quite

objectionable. Also when these carbides are dislodged from the matrix they can cause 3 body abrasive wear. If, however, the size of these carbides can be reduced [few microns or less], then, their potential to produce long chips will be minimal and even when they are dislodged from the matrix, may just cause polishing action instead of abrasive wear.

Segregation of carbides can result in large areas of softer matrix which are potential regions for adhesion. During high speed sliding, adhesion in these large areas can yield large sized adhesive wear fragments and can accelerate galling. On the other hand a more uniform distribution of carbides will reduce the regions of softer matrix material considerably and hence may be capable of reducing the extent of adhesive wear and ultimately galling wear.

COMPARATIVE STUDY OF A TOOL STEEL MADE BY TWO DIFFERENT METHODS

In the first part,results of Scanning Electron Micrographic study of polished and etched surfaces of both CPM and conventional materials will be presented. Following this results of pin on disk tests will be presented.

Fig. 1 (a) is a Scanning Electron Micrograph (SEM) of a representative group of as atomized particles used to make the steel by compaction and particle metallurgy technique (CPM). While the surfaces of individual particles appear smooth in Fig. 1 (a), considerable texture is revealed at higher magnification. It may be noted that many of the particles are spherical in shape. These particles are cooled at very high rate which results in many individual carbides of very small size within each particle.

Fig. 2 (a) is a photo micrograph of individual carbides in a quenched and tempered CPM sample while Fig. 2 (b) is a corresponding photomicrograph of quenched and tempered conventional steel (CON). The carbides in Fig. 2 (a) are not only seen to be smaller than those in Fig. 2 (b) but they are more uniform in size and shape and more uniformly distributed.

Fig. 3 (a) as a SEM of a highly finished CPM steel (produced by conventional surface grinding with spark off) showing uniform distribution of carbides in the matrix. Fig. 3 (b) is a SEM of part of this area at higher magnification. A very thin layer of matrix material appears to have been smeared over the surface uniformly. In addition several small voids ($\sim 1\ \mu$ size) due to dislodgement of carbides can also be seen.

Fig. 4 (a) is a SEM of a highly finished CON steel (produced by conventional surface grinding with spark off) showing segregation of carbides and presence of large areas of softer matrix material. Fig. 4 (b) is a SEM of part of this area at higher magnification. The layer of matrix material smeared over the surface appears to be a lot thicker than in the case of CPM material. In addition larger sized voids due to carbide dislodgement can can clearly be seen. These large sized carbides dislodged from the matrix can cause abrasive wear due to 3 body abrasion. Surface finish measurements using a Talysurf instrument indicated the CLA value of the CON steel to be 1.2 μ in. In comparison the CLA value for the CPM material was found to be inferior and about 2.3 μ in. The superior finish obtainable with CON steel appears to be due to smearing of the matrix material during spark off operation. This aspect has been studied further by etching the surface layers of these two types of material and examining them in a SEM.

Fig. 5 (a) is a SEM of an etched CPM steel showing very little difference in the distribution of matrix as compared to the polished surface [see Fig. 3 (a)], although the density of the second phase carbides can be seen to be higher on the surface. Fig. 5 (b) is a SEM of the same surface at higher magnification. In contrast, the etched CON steel showed marked difference before and after etching. Fig. 6 (a) is a SEM of an etched CON steel showing no segregation of carbides and absence of large areas of matrix material [compare with Fig. 4 (a)]. Fig. 6 (b) is a SEM of this surface at higher magnification showing the presence of carbides in a wide range of size.

DISCUSSION

The superior finish obtainable with CON steel as compared to CPM steel has prompted us to investigate the possible reasons for this difference. SEM examination showed clearly large areas of smooth matrix material with CON steel as compared to CPM material. Examination of the etched surface of CON steel, confirmed the reason for the large areas of matrix material to be due to smearing of this material on the surface. Presence of large voids on the CON steel indicate that carbides in this area are dislodged and may cause, during service, abrasive wear due to 3 body abrasion. This will not be the case with CPM material due to small size carbides which may just cause polishing action instead of abrasive wear. Two important questions arise as a result of this study. First, is it necessary or even desirable to have a high finish for the bearing members in sliding contact if it results in large areas of softer matrix material? Second, if the high finish is not desirable from the point of galling, then should the bearing material be manufactured using CPM technique instead of the conventional method for superior wear resistance?

Further work should answer these questions more accurately.

FUTURE WORK

Pin-on-disk tests will be conducted to compare the tendency for galling for the conventional and CPM material. Two high speed tool steels (AISI T-15 and AISI M42) will be used in these studies. Rubbing tests will be conducted first on the disks of the two types of material that are ground to the best attainable finish. This will be followed by rubbing tests on the etched disks.

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1. R. Komanduri and M. C. Shaw, "Wear Mechanics in High Speed Sliding Contact," First Annual Report to the Office of Naval Research, Sept. 1975.
2. E.J. Dulis, and T. A. Neumeyer, "Particle-Metallurgy High Speed Tool Steel", Proc. of the Conf. on Materials for Metal Cutting, ISI P126, April 1970, The Iron and Steel Institute, U. K.

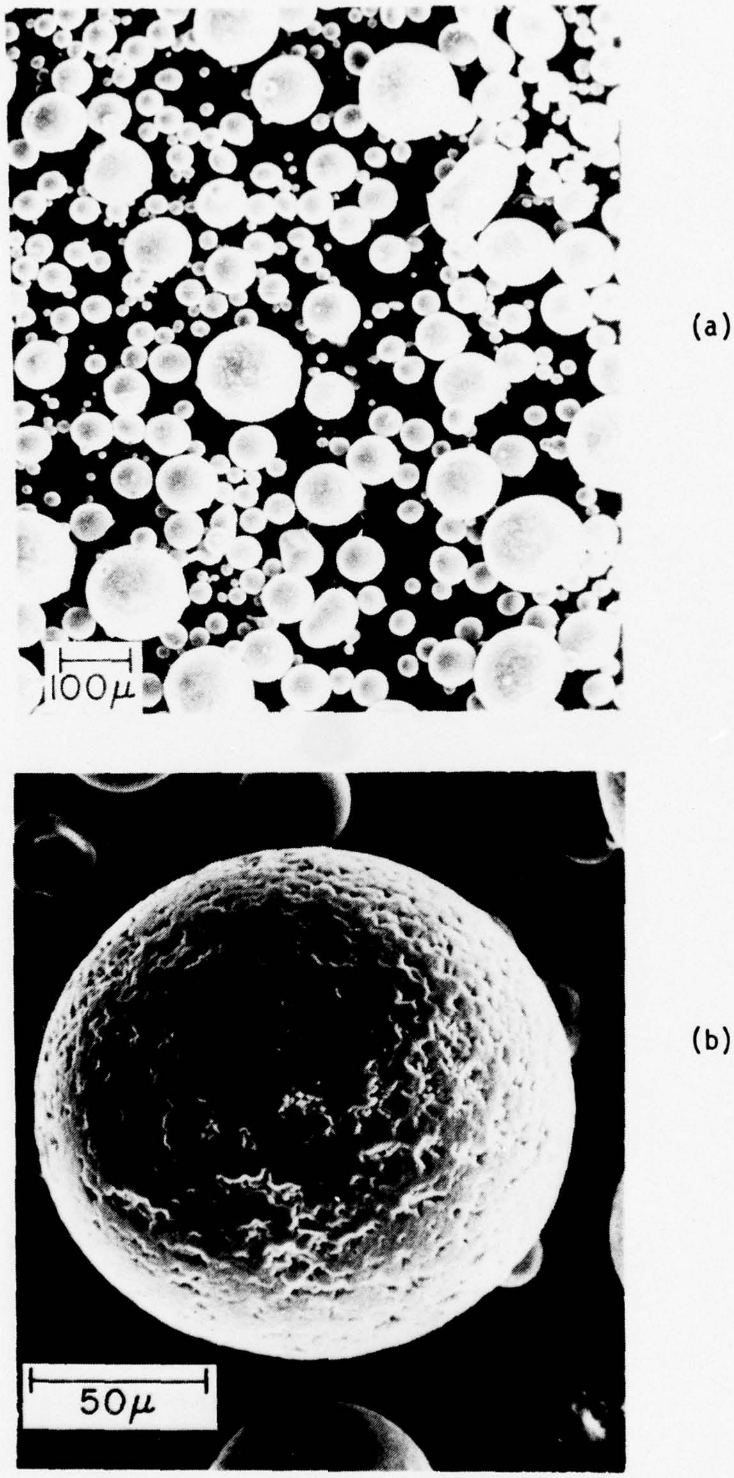
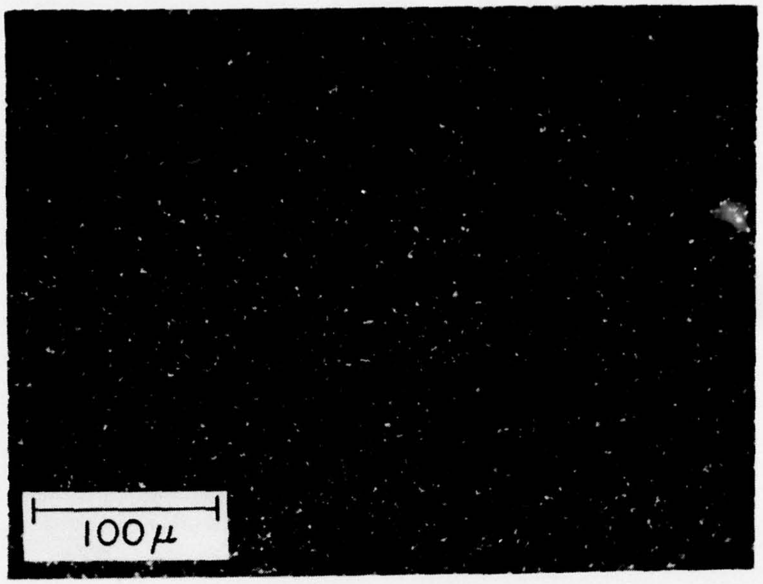
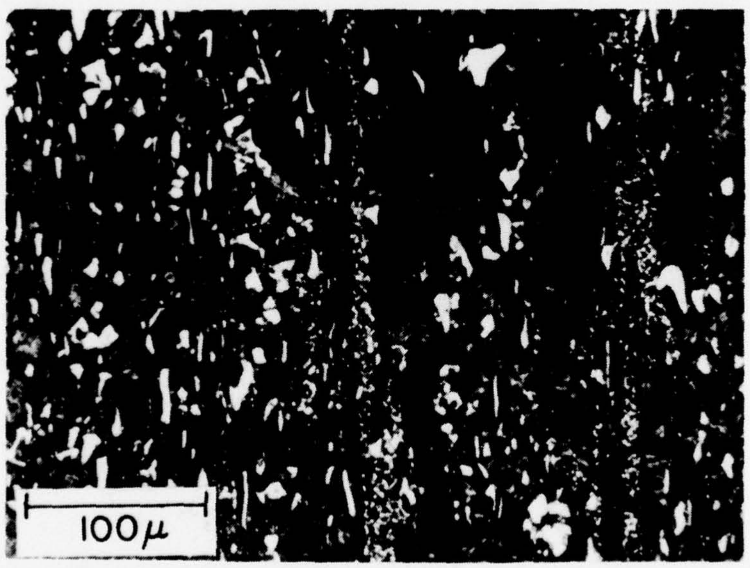


Fig. 1. Micrographs of as atomized particles of AISI T-15 tool steel.



(a)

Median Carbide Size 1.3μ
Maximum Carbide Size 3.5μ

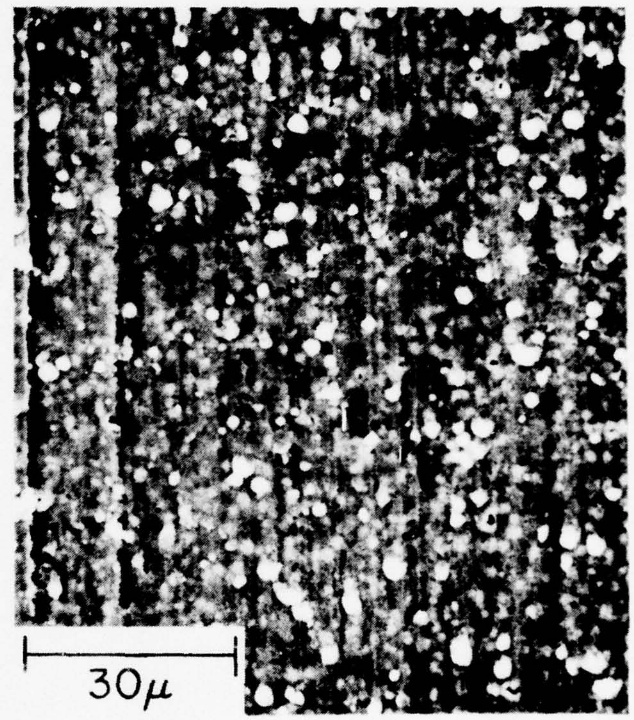


(b)

Median Carbide Size 6.2μ
Maximum Carbide Size 34μ

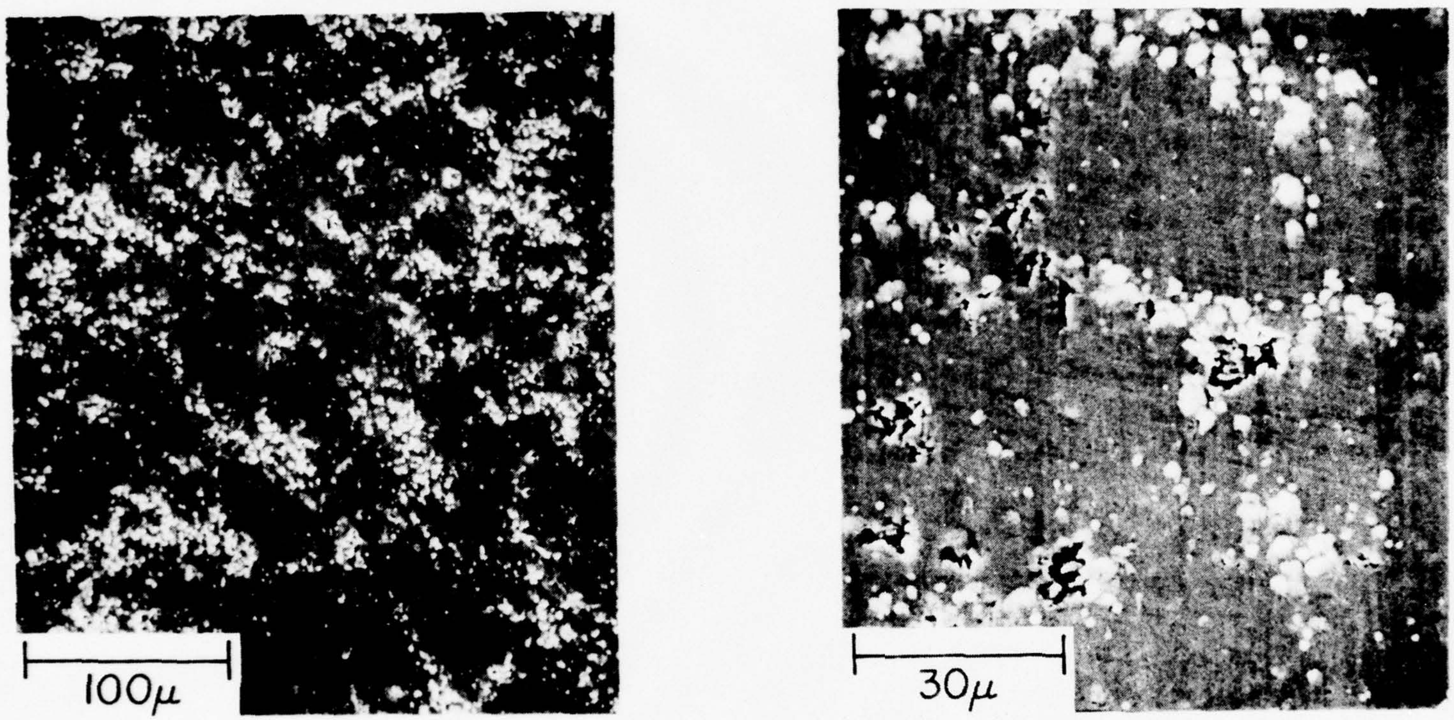
Fig. 2. Microstructure of AISI T-15 tool steel (quenched and tempered) produced (a) from particles and (b) by the conventional technique. (picral etch) (Courtesy Crucible Steel Co.)

(a)



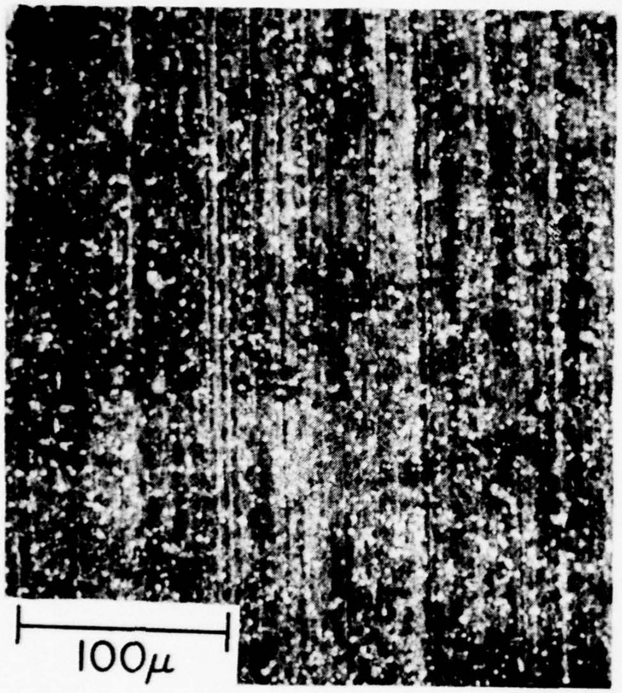
(b)

Fig. 3. SEM of the surface of CPM steel, showing uniform distribution of carbides in the matrix.

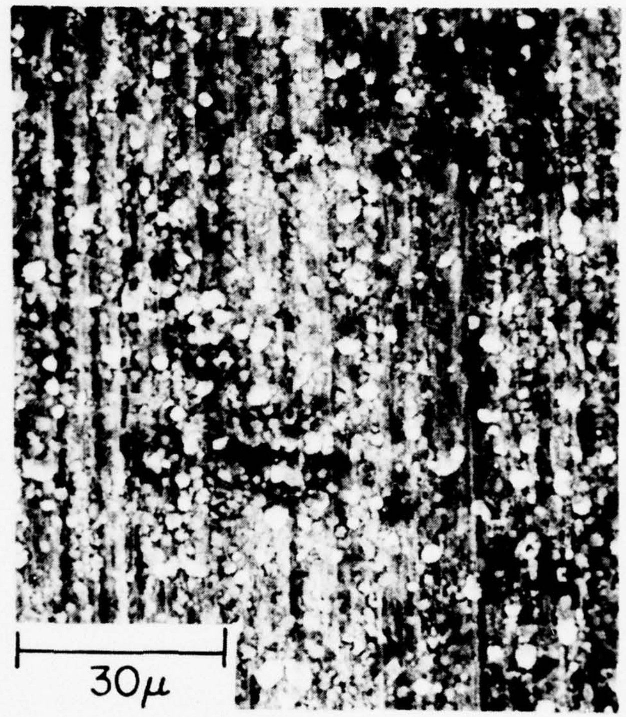


(a) (b)

Fig. 4. SEM of the surface of CON steel, showing segregation of carbides and presence of large voids due to carbides dislodgement.

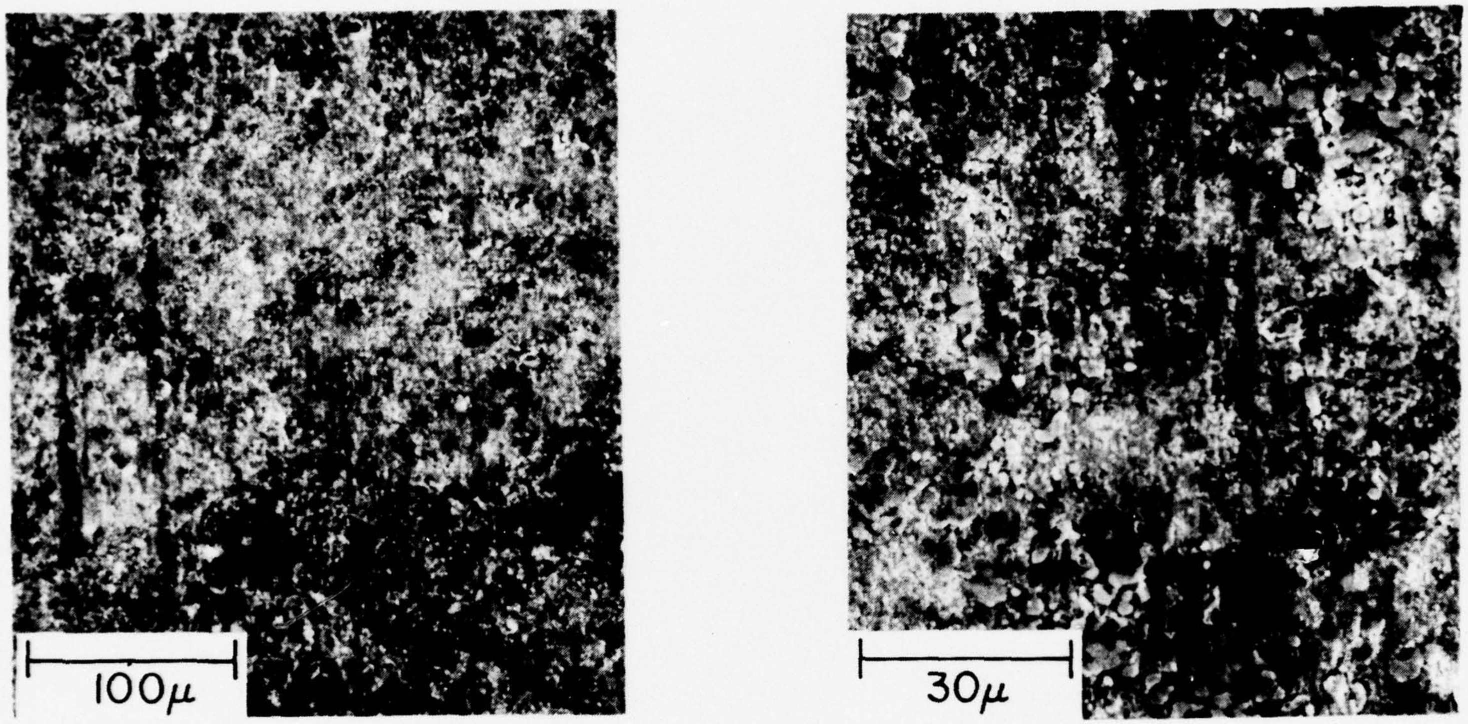


(a)



(b)

Fig. 5. SEM of the etched surface of CPM steel, showing a uniform distribution of carbides in the matrix.



(a) (b)

Fig. 6. SEM of the etched surface of CON steel, showing absence of large areas of matrix material present on the polished surface and presence of carbides of wide range in size.

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A MECHANISM FOR THE ACCELERATED WEAR OF HIGH SPEED SLIDING SURFACES IN THE PRESENCE OF SPHERICAL PARTICLES

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(Received July 22, 1976)

Summary

A mechanism for the accelerated wear of bearing surfaces due to the cutting action of the spherical particles between bearing surfaces in sliding contact is proposed and verified experimentally.

Introduction

Although spherical particles have been observed in grinding debris for a long time [1], it is only since 1970 when Scott and Mills [2] first reported the observation of spherical wear particles on the surface of fatigue cracks formed on ball bearings that had been subjected to rolling contact fatigue that interest has grown as to its mechanism of formation and the implication of accelerated wear once the spherical particles have been formed.

Stowers and Rabinowicz [3] observed spherical wear particles in their fretting corrosion studies in which silver oscillates on silver at low frequency in the absence of a lubricant. They observed both cylindrical and spherical particles and suggested that these particles may roll between the sliding surfaces and reduce the coefficient of friction in a manner similar to ball and roller bearings. In a recent paper, Komanduri *et al.* [4] established Stowers and Rabinowicz's hypothesis experimentally that the micron-sized particles in sliding contact do in fact reduce the static coefficient of friction as with large-sized ball and roller bearings. Based on this, it appears that the presence of spherical particles between bearing surfaces in sliding contact may in fact be advantageous since they may reduce friction as in the case of the static friction results.

Middleton *et al.* [5] found spherical wear particles in jet engine lubricating oil and found their number to increase with bearing deterioration. Seifert and Westcott [6] used a magnetic device that separates metallic wear particles from oil to produce a spectrum of particle sizes in what is referred to as a ferrogram. Based on the above work, Scott and Mills [7]

proposed that the increase in the number of spherical particles present in an oil sample be considered as a potentially useful diagnostic tool for detecting the failure of high speed ball bearings. This implies that wear progresses at an accelerating rate owing to the presence of the spherical particles between bearing surfaces in sliding contact and contradicts the static experimental results of lower friction coefficient and consequently lower wear. Further, although Scott and Mills proposed that the presence of an increasing number of spherical particles in the lubricating oil be used as a tool for detecting the failure of bearing surfaces, no mechanism was proposed to explain this accelerated wear resulting from the presence of these spherical particles in between the bearing surfaces in sliding contact. In this paper a mechanism for this accelerated wear of bearing surfaces, due to cutting action by the spherical particles between bearing surfaces in sliding contact, is proposed and verified experimentally.

Although the static friction experiments with spherical particles gave lower friction coefficients, as with large-sized balls and rollers in a bearing, the experiments to be reported here under dynamic conditions gave higher wear and a higher coefficient of friction with spherical particles than without An explanation for this difference in the static and dynamic test results is also presented; it is based on the fact that the spherical particles are free to move over large distances with large mechanical interaction (considerable depth of cut) unlike in ball and roller bearings, resulting in chip formation, subsurface plastic deformation and higher wear.

Experimental set-up and test procedure

The pin-on-disc apparatus used in this study to determine the coefficient of friction and wear of bearing surfaces, with and without the spherical particles in high speed sliding contact, is the same as the one reported by Lal *et al.* [8]. Figure 1 shows a schematic of the experimental set-up used. The disc is driven by the spindle of an inverted drill press while the stationary pin is attached to a horizontal arm having strain gages for measuring the frictional .orce. A hardened AISI 52100 circular steel plate (R_c 65) was used as the disc and a hardened AISI 52100 steel ball of diameter 3/16 in and a 120° cone angle were used as the pins. The disc was finely ground and the pin polished first with a 3 μm diamond paste and then with a 0.05 μm gamma alumina polish. In order to study the effect of one of the bearing surfaces being soft in sliding contact, a high speed tool steel (AISI M2) pin of diameter 3/16 in was used in the annealed condition. Spherical particles in three size ranges, namely 30 - 45 μm, 45 - 60 μm and 60 - 75 μm, of AISI M2 tool steel produced by atomizing a molten metal in an inert atmosphere [4] were used in the present investigation. The particles were sized using a micromesh sieve and a vibrating table. Tests were conducted at 1000 ft min^{-1} and 2 lb normal load using a lubricant for a constant period of time (10 min) or for a constant sliding length (10 000 ft). A slurry of spherical

TABLE 1

Test results

Pin	Size of spherical particles (μm)	Coefficient of friction		Wear volume on the pin ($\times 10^6$) (in^3)	
		With spherical particles	Without spherical particles	With spherical particles	Without spherical particles
High speed steel 1/8 in pin (annealed)	20 - 30	0.1313	0.0688	small	negligible
3/16 in diameter AISI 52100 hardened balls	20 - 30	0.2063	0.0563	3.619	1.526
AISI 52100 hardened truncated cone	30 - 45	0.1656	0.0625	4.0961	negligible
	45 - 60	0.1344		1.8888	
	60 - 75	0.1663		5.1739	

The disc was AISI 52100 (hardened), the load 2 lb, the speed 1000 ft min^{-1} and the sliding distance 10 000 ft, with lubricant.

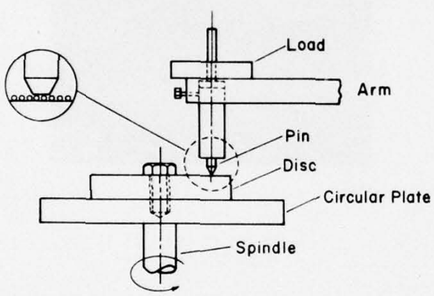
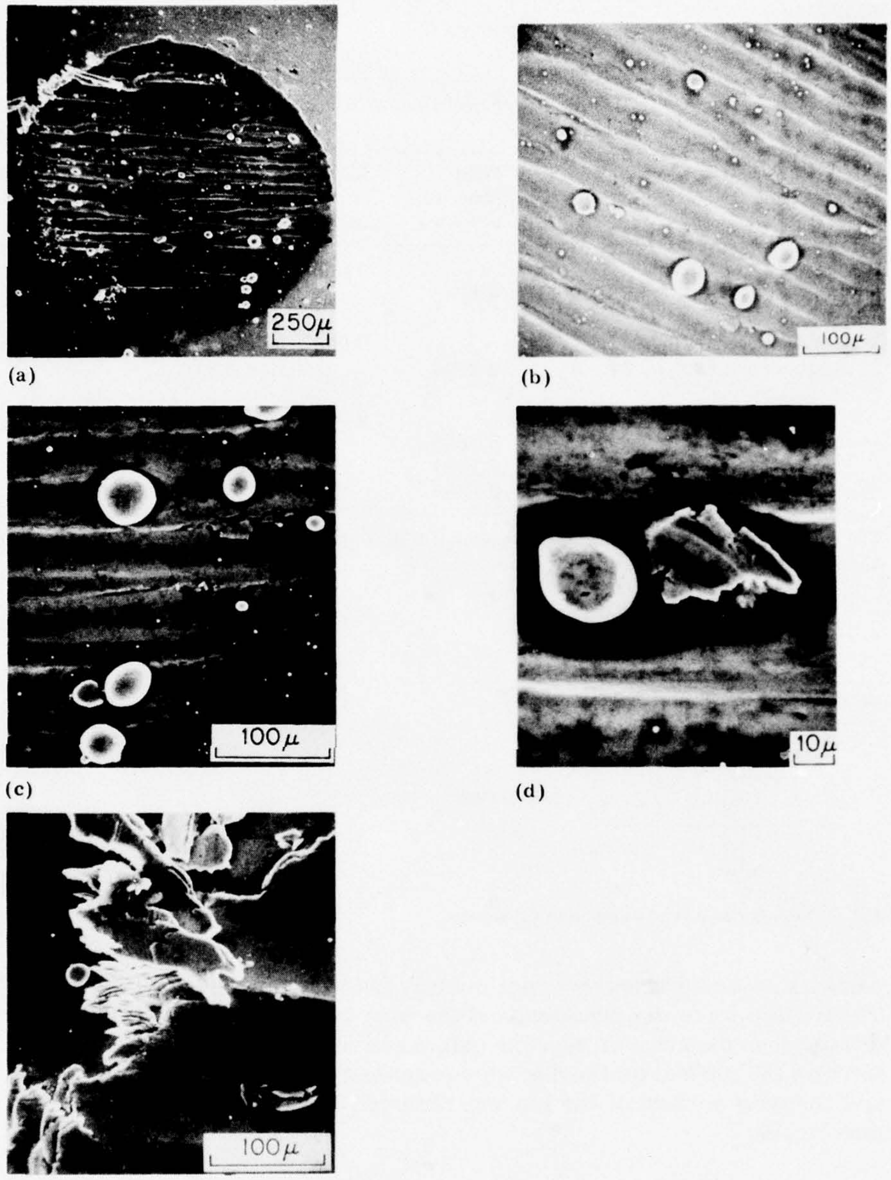


Fig. 1. Schematic of the experimental set-up.

particles in the lubricant was continuously fed to the interface during a test. The friction force was measured and the wear volume determined from the difference in diameter of the cone before and after the test. The wear surfaces on the pin and on the disc were examined under an optical microscope and the wear surface of the pin was observed in a scanning electron microscope.

Test results

Table 1 summarizes the test results, where it can be seen that the wear and the coefficient of friction are greater with the spherical particles than without. Also, wear with larger-sized spherical particles (60 - 75 μm) was



(a) (b) (c) (d) (e)

Fig. 2. (a) Plan view micrograph of a hardened AISI 52100 truncated conical pin showing the grooves made by the spherical particles. (b), (c) Individual grooves of different widths made by spherical particles of different diameters. (d) Microchip possibly generated by a spherical particle. (e) Leading edge of the pin (shown in (a)) showing chips generated by the spherical particles.

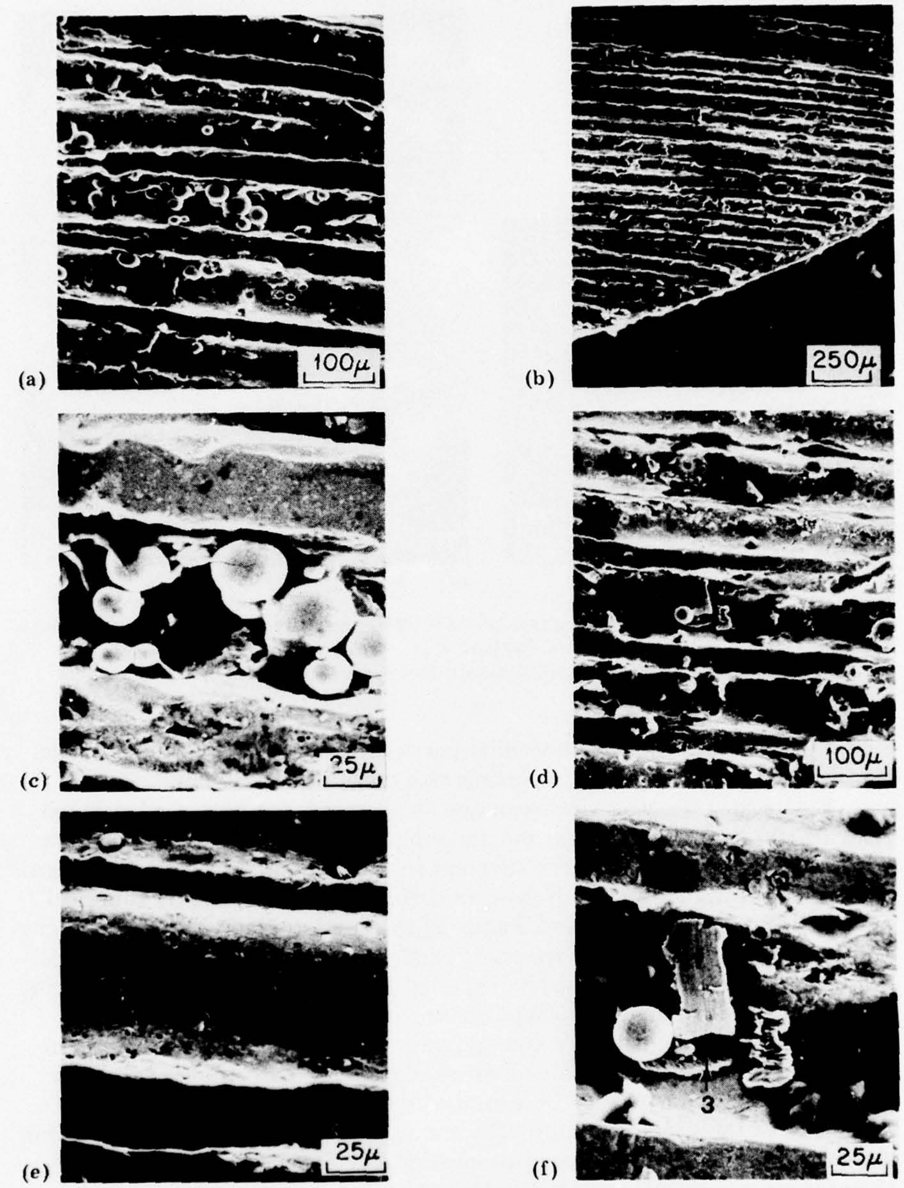
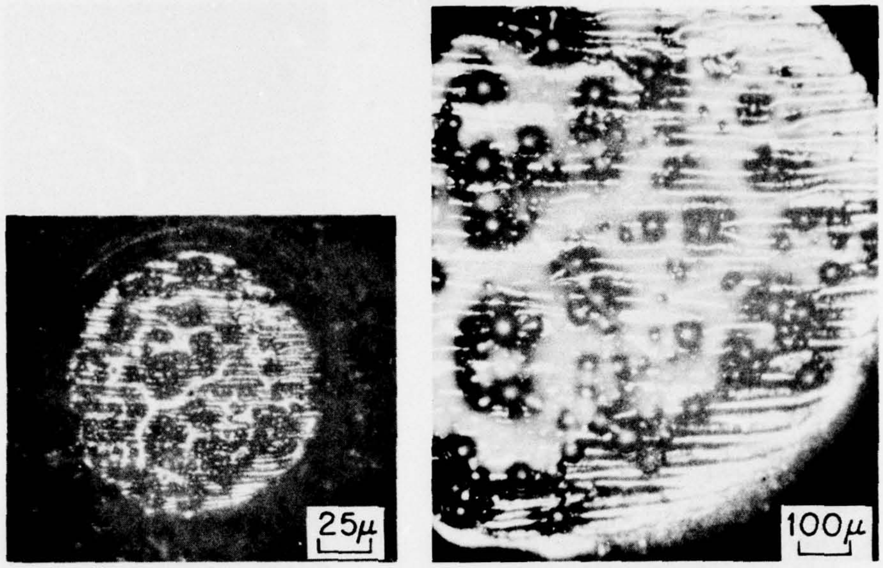


Fig. 3. (a) Series of grooves made by the spherical particles (20 - 30 μm) on an annealed AISI M2 tool steel. (b) Micrograph showing several spheres trapped in each groove, indicating that some of the grooves were made not by a single sphere but by a group of spheres. (c) Group of spheres in a groove at higher magnification. (d) Micrograph of a groove showing several chips generated in the groove. (e) Higher magnification of part of (a) showing three chips near a sphere. (f) Micrograph of part of the groove showing severe plastic deformation in the groove generated by the spherical particles.



(a) (b)

Fig. 4. (a) Plan view optical micrograph of AISI 52100 hardened pin showing wear tracks using 45 - 60 μm spherical particles. (b) Part of the pin shown in (a), showing grooves whose paths change as different spherical particles move through them.

found to be greater than with smaller particles (30 - 45 μm) with a possible transition in the wear rate at a particle size range of 45 - 60 μm.

Figure 2(a) is a plan view scanning electron micrograph of a hardened AISI 52100 truncated conical pin showing the spherical particles and the grooves made by them. Figures 2(b) and (c) are micrographs at higher magnifications showing individual grooves of different widths made by spherical particles of different diameters. Figure 2(d) is a micrograph showing a microchip possibly generated by a spherical particle and Fig. 2(e) is a micrograph at higher magnification of the leading edge of the pin (see Fig. 2(a)) showing chips generated by the spherical particles.

Figure 3(a) is a plan view micrograph of the AISI M2 tool steel pin in the annealed condition, showing a series of grooves made by the spherical particles (20 - 30 μm). It can be seen that the grooves are wider than the diameters of the spheres. Figure 3(b) is a micrograph at higher magnification showing several spheres trapped in each groove, indicating that some of the grooves were made not by a single sphere but by a group of spheres. Figure 3(c) shows a group of spheres in a groove at higher magnification. Figure 3(d) is a micrograph of a groove showing several chips generated in the groove and Fig. 3(e) is a higher magnification micrograph showing three chips (1, 2, 3) near a sphere. The micrograph of chip 1 in Fig. 3(e) is for the underside of the chip, while chips 2 and 3 show undulations on the top side

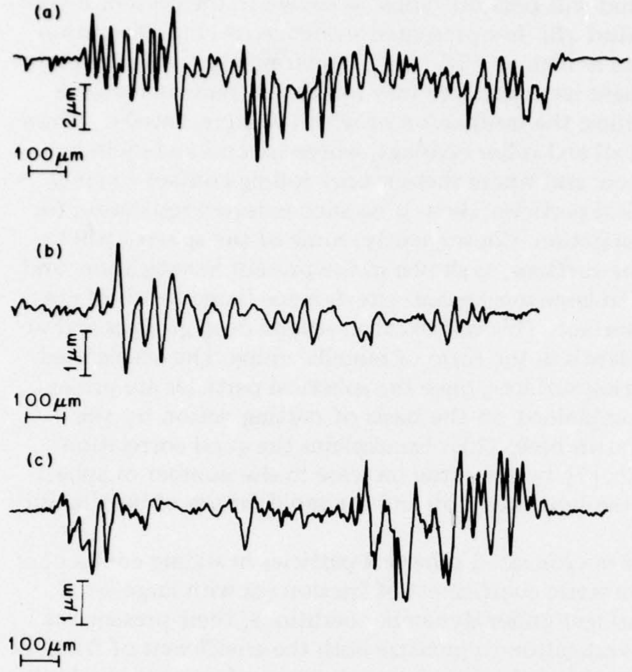


Fig. 5. Talysurf traces across the wear tracks made on the disc by hardened AISI 52100 truncated cones in the presence of spherical particles of the following sizes: (a) 30 - 45 μm; (b) 45 - 60 μm; and (c) 60 - 75 μm.

of the chips. Figure 3(f) is micrograph of part of the groove showing severe plastic deformation in the groove generated by the spherical particles.

Figure 4(a) is a plan view optical micrograph of a hardened AISI 52100 pin using 45 - 60 μm spherical particles and Fig. 4(b) is part of the pin at higher magnification showing grooves whose paths change as different spherical particles move through them.

Figures 5(a) - (c) are Talysurf traces across the wear tracks made on the disc by hardened AISI 52100 truncated cones in the presence of spherical particles of three different sizes (see Table 1 for details). It can be seen from Fig. 5 that, while some individual grooves have about the same diameter as the spherical particles within each wear track on the disc, there are others which are caused by a series of spherical particles.

Discussion

Although the hard spherical particles between bearing surfaces in sliding contact present very high negative rake angles, under high normal force

these spheres can [8] and will generate chips, as shown in the present investigation. In fact Komanduri [8] has presented evidence of chip generation with negative rake angles as high as $-76°$. In a similar manner, abrasive grains in a grinding wheel present large negative rake angles and remove metal in the form of extruded chips, the mechanism of which was presented by Shaw [9] elsewhere. Unlike ball and roller bearings, where spheres and cylinders are retained between races and where there is only rolling contact (mainly elastic) involving spherical particles, there is no such external restriction for the spheres of this investigation. Consequently, some of the spheres will be anchored into one of the surfaces, as shown in the present investigation, and will generate chips due to large mechanical interference (large depth of cut) from the other sliding surface. This will result in several deep grooves and in large amounts of wear debris in the form of metallic chips. The accelerated wear and failure of bearing surfaces, once the spherical particles are present between them, can be explained on the basis of cutting action by the spherical particles, as shown here. This also explains the good correlation found by Scott and Mills [7] between the increase in the number of spherical particles present in the lubricating oil and the rapid failure of bearing surfaces.

Also, although the micron-sized spherical particles in sliding contact are found [4] to reduce the static coefficients of friction (as with large-sized balls and rollers in bearings) under dynamic conditions, their presence is found in the present investigation to increase both the coefficient of friction and wear. The reason for this difference lies in the type of contact involved. While the contact between sliding members in the presence of spherical particles under light load and low speed is mainly elastic, that under dynamic conditions at high speed involves subsurface plastic deformation and chip formation. The latter causes high friction (as in metal cutting) and rapid wear.

Conclusions

(1) Small micron-sized hard spherical particles between sliding surfaces are found to generate chips and high wear.

(2) The coefficient of friction under dynamic conditions was found to be higher than at slow speed. This is explained on the basis of the type of contact (subsurface deformation and chip formation in the former case and elastic contact in the latter).

(3) Cutting action is suggested to be the cause of the rapid wear of bearing surfaces once spherical particles are present between them.

Acknowledgments

This work was sponsored by the Office of Naval Research (ONR). The authors wish to thank Dr. K. E. Ellingsworth and Lt. E. S. Miller of ONR

for their interest in this work. The spherical particles used in this study were generously provided by the Crucible Materials Research Center, Colt Industries, Pittsburgh, Pa. The authors thank Messrs. E. J. Dulis and T. A. Neumeyer for providing the samples of spherical particles. AISI 52100 discs and pins used here were generously heat-treated by Timken Company, Ohio, and the authors thank Dr. W. Littman, Director of Research at Timken Co. for arranging this. Some of the tests were conducted by Mr. S. Lakshmipathy and the authors gratefully acknowledge his contribution.

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Short Communication

The role of spherical particles as friction reducers in sliding contact

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Micron-sized spherical particles in sliding contact are found to reduce the static coefficient of friction, as with the case of larger-sized balls and rollers in bearings.

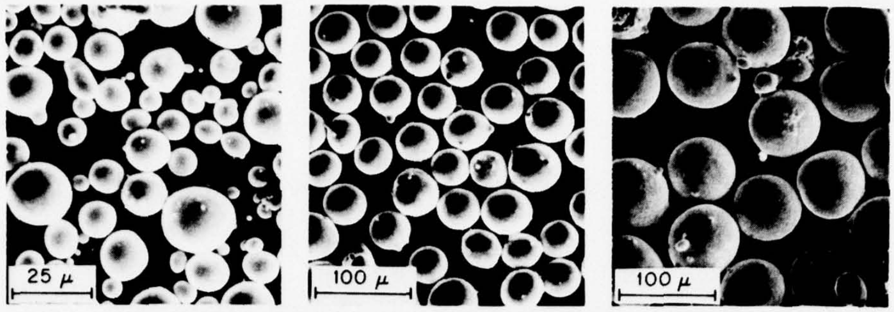
Introduction

Spherical wear particles were found by Scott and Mills [1, 2] on the surfaces of fatigue cracks formed on ball bearing components that had been subjected to rolling fatigue, and in jet engine lubricating oil [3] as metallic wear particles. The number of these particles was found to increase with bearing deterioration. Scott and Mills suggested the use of this information as a diagnostic tool for anticipating the fatigue failure of high speed ball bearings.

Spherical particles were also generated in a cavitation erosion apparatus [4], in grinding [5] and in fretting corrosion studies [6], to investigate the mechanism of their formation. Stowers and Rabinowicz, in their fretting corrosion studies, wherein silver oscillates on silver at low frequency, observed cylindrical particles in addition to spheres. They suggested that these micron-sized spherical and cylindrical particles may roll between the sliding surfaces and thus reduce the coefficient of friction as with ball and roller bearings. In this brief communication, the authors present data establishing that micron-sized spherical and cylindrical particles do in fact reduce the static coefficient of friction.

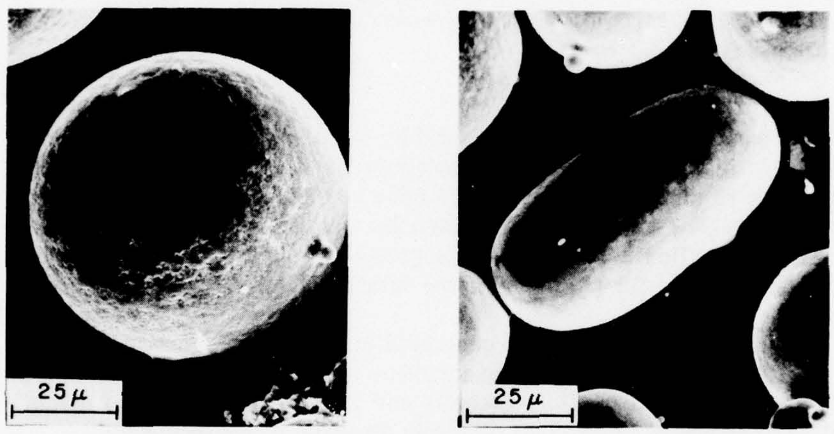
Experimental set-up

Micron-sized spherical particles of AISI M2 tool steel were produced by atomizing the molten metal in an inert atmosphere; this is the first stage in the manufacture of CPM tool steel made by the particle metallurgy technique [7]. The spherical particles were sieved to obtain three size ranges, namely 20 - 30 μm, 45 - 60 μm and 75 - 90 μm, using a micromesh sieve and a vibrating table. Figures 1(a) - 1(c) are scanning electron micrographs showing the size distribution of particles in these three size ranges, respectively. It can be seen from Fig. 1 that, while there is some variation in size in



(a) (b) (c)

Fig. 1. Scanning electron micrography showing the size distribution of spherical particles in three different size ranges: (a) 20 - 30 μm; (b) 45 - 60 μm; (c) 75 - 100 μm.



(a) (b)

Fig. 2. (a), (b) Typical micron-sized spherical and cylindrical particles formed by the atomization technique showing details of surface morphology at higher magnification.

the lowest size range considered here, in the two other ranges the variation in size is small and the particles are of nearly uniform size. In so far as friction between rolling of these particles and the sliding surfaces are concerned, it is the maximum size that counts. Figures 2(a) and 2(b) show, at higher magnification, typical micron-sized spherical and cylindrical particles formed by the atomization technique. They also show details of the surface morphology which are similar to those reported by Stowers and Rabinowicz.

Figure 3 shows the experimental set-up used to determine the coefficient of friction by measurement of the angle of repose (dry) with and without spherical particles rolling between a glass plate and a gage block. No lubricant was used in this study as preliminary tests with a lubricant gave

TABLE 1

Load (g)	With spherical particles			Without spherical particles	
	Particle size range (μm)	Coefficient of friction μ	Angle of repose α ($^\circ$)	Coefficient of friction μ	Angle of repose α ($^\circ$)
31.5	20 - 30	0.054	3.067	0.117	6.667
9.5	20 - 30	0.035	2.033	0.094	5.367
3.2	20 - 30	0.026	1.520	0.089	5.100
31.5	45 - 60	0.027	1.582		
9.5	45 - 60	0.018	1.012		
3.2	46 - 60	0.012	0.69		
31.5	75 - 90	0.022	1.267		
9.5	75 - 90	0.009	0.506		
3.2	75 - 90	0.007	0.379		

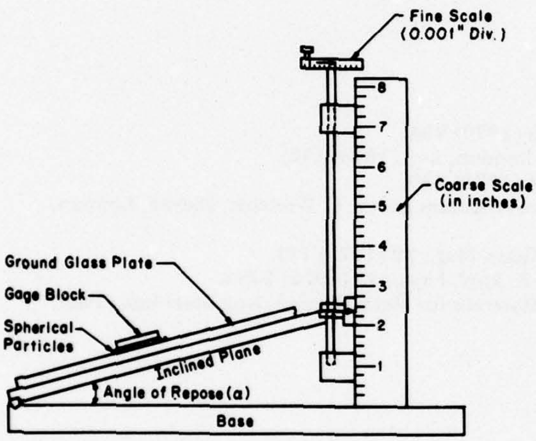


Fig. 3. Inclined plane experimental set-up used to determine the coefficient of friction.

very inconsistent results, possibly due to the differences in thickness of the lubricant in different tests. The gage block was placed on the glass plate with or without spherical particles between the surfaces and one end of the glass plate was slowly raised (the other end being hinged to the base) until the gage block just began to slide. A vibrator having a frequency of 60 Hz was attached to the glass plate to avoid stick–slip. The angle of repose and hence the coefficient of friction was calculated by observing the height of the specimen which was causing the sliding. The coefficient of friction was determined for three different loads and for three size ranges of the spherical particles.

Test results and conclusions

The results of the tests are presented in Table 1. At least three tests were performed for each test condition and the results averaged. It can be seen from Table 1 that the coefficient of friction is higher without spherical particles than with spherical particles, as Stowers and Rabinowicz postulated, for all the loads and the sizes of the spherical particles used in this study. Also, for a constant particle size range, friction increases with the load. At a constant load the static coefficient of friction decreases with increase in the spherical particle size.

Acknowledgments

This work was sponsored by the Office of Naval Research (ONR). The authors thank Dr. K. E. Ellingsworth and Lt. R. S. Miller of ONR for their interest in this work. The spherical particles used in this study were generously provided by the Crucible Materials Research Center, Colt Industries, Pittsburgh. The authors thank Messrs. E. J. Dulis and T. A. Neumeyer for providing the samples of spherical particles.

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Formation of spherical particles in grinding

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ABSTRACT

Spherical metal particles in the size range of $\frac{1}{3}$ to 60 μ found when grinding chips are examined in the scanning electron microscope and a mechanism for their formation based on surface energy is presented.

§ 1. INTRODUCTION

Spherical wear particles were first reported by Scott and Mills in 1970. These particles, which ranged in size from 1 to 20 microns, were found on the surfaces of fatigue cracks formed on ball bearing components that had been subjected to rolling contact fatigue. It was suggested that the spheres were formed from platelets of metal removed by cavitation erosion when the lubricant entrapped in fatigue cracks was suddenly released. These platelets or tongues of metal rolled up to form spheres. Some spheres were observed to be smooth and some had a layered structure as revealed in the scanning electron microscope (SEM). Subsequent investigations using X-ray energy dispersion analysis in the SEM as well as micro-probe analysis have shown that the spheres are particles of the bearing steel and not irrelevant artifacts (Scott and Mills 1973 a, b).

Spherical wear particles have also been found in jet engine oil using a magnetic device that removes metallic wear particles from oil to produce a spectrum of particle sizes in what is referred to as a ferrogram (Seifert and Westcott 1972). The number of spherical particles in used engine oil is found to increase as ball bearing fatigue progresses (Middleton, Westcott and Wright 1974). It is thought that spheres form in increasing numbers as fatigue cracks grow and that the number of spheres present in an oil sample may be potentially useful as a diagnostic tool for anticipating the surface fatigue failure of high speed ball bearings (Scott and Mills 1973 a, b).

Doroff, Miller, Thiruvengadam and Westcott (1974) have observed spherical particles when aluminium and steel were tested in the ASTM standard vibratory cavitation erosion apparatus. These tests prove that spherical particles can be produced by cavitation and support the cavitation theory of spherical particle generation during rolling contact fatigue crack formation.

Loy and McCallum (1973) have presented an alternative explanation to the cavitation mechanism of Scott and Mills (1970). They suggest that spheres form during the subsurface crack-formation associated with rolling fatigue. When two cracks that are laterally displaced approach each other a knot of

highly-work hardened material forms between the ends of the cracks and the cracks subsequently take a circular path around the knot thus forming a circular particle. SEM micrographs have been presented to support this theory of sphere formation.

There is no apparent reason why both of the proposed mechanisms of sphere formation cannot be operative during ball bearing fatigue. Both mechanisms would be consistent with the observation that the number of spheres present in the lubricant increases with bearing deterioration.

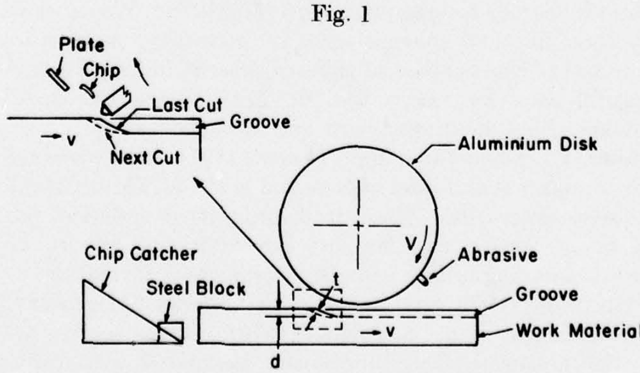
Spherical wear particles have also been observed in fretting corrosion studies in which silver oscillates on silver at low frequency in the absence of a lubricant (Stowers and Rabinowicz 1972). In addition to spheres, cylinders were also formed. The spherical and cylindrical wear particles were found to roll between the sliding surfaces and appeared to reduce the coefficient of friction. Spherical particles were not observed when copper, low-carbon steel or high-strength steels were operated on like surfaces under conditions resulting in fretting corrosion, or when silver was operated on silver at high oscillating frequencies.

The object of the present investigation is to present evidence that spherical chips having a wide variety of morphologies and sizes are formed in fine grinding and to suggest a mechanism, based on surface energy, for the observed curling of grinding debris.

§ 2. Spherical particles generated in abrasive processing

Spherical particles representing a wide variety of morphologies have been observed when the ' chips ' from an abrasive process are examined in the SEM. In the examples which follow a single abrasive particle mounted in the periphery of a disc was used in order to facilitate chip collection and to avoid the presence of extraneous bond and abrasive particles in the sample of metallic chips. The test arrangement is shown in fig. 1. The metallic sample was adjusted to interfere slightly with the rotating abrasive particle and then fed horizontally. The abrasive particle encounters the metal many times as it generates a shallow groove in the metal plate. The ' chips ' are collected on a catcher made of paper. The latter was placed on a magnetic table and a piece of steel was kept

Fig. 1

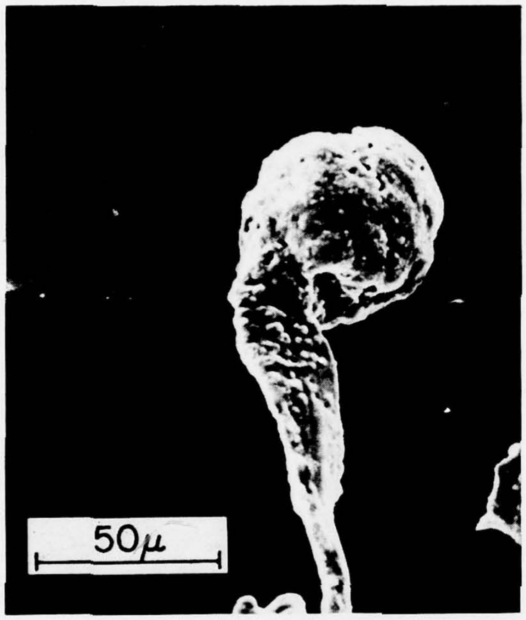


Schematic diagram of the test set-up.

over the catcher to hold it in position. The settings of the machine may be adjusted so that the mean undeformed thickness of individual layers removed is a micron or less which corresponds to the situation in fine-grinding operation.

Unless otherwise noted the abrasive was a small ($\sim \frac{1}{3}$ mm diameter) crushed particle of hot-pressed high-density silicon nitride and the metal was hard

Fig. 2



(*a*)

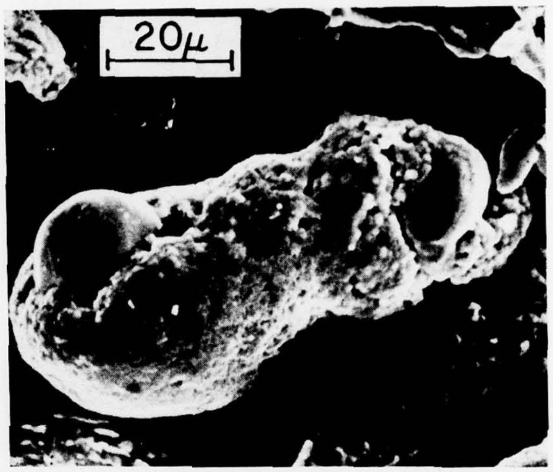
(*b*)

(*a*)–(*b*) Chips that are partially curled in three dimensions into crude spheres.

(Rockwell 66·5 in the C scale) AISI T-15 tool steel produced by the particle metallurgy technique. The surface speed of the abrasive was 15 m/sec (3000 f.p.m.) in all cases.

The particles produced were thin flat platelets many of which curled up immediately upon being generated, or wrapped tightly around other adjacent particles to form a cocoon-like enclosure. Figures 2 (*a*) and (*b*) show platelets that are partially rolled or curled in three dimensions into crude spheres. Several small secondary chips can be seen in fig. 2 (*b*), which Scott and Mills (1970) termed ' tongues of metal '. Figure 3 shows a platelet that has curled around other particles (some of which are spherical) to form a cocoon-like enclosure, while fig. 4 shows a similar action that has resulted in a more nearly spherical shape.

Fig. 3



A platelet that has curled around other particles (some of which are spherical) to form a cocoon-like enclosure.

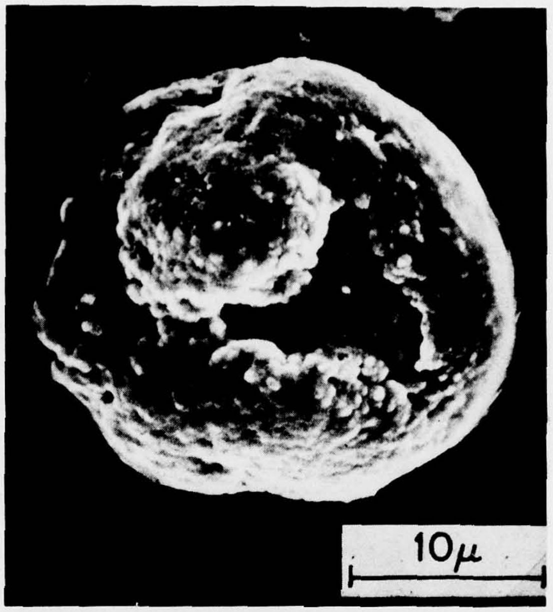
In many other cases individual platelets were small and covered a small area of the sphere of which they became a part. In such cases the outer surface of the sphere consisted of layer on layer of overlapping platelets. Figure 5 gives examples of this type of sphere formation in which the individual platelets are progressively smaller and the resulting sphere more nearly perfect. The spheres resulting from this action were frequently hollow.

In some instances spheres that had been built up by the deposition of many particles appeared to round up and become smoother as the individual particles coalesced into a single particle. In these cases the temperature of the particle was sufficiently high to enable sintering to take place as surface forces tended to produce a smoother surface. Figure 6 illustrates this action.

Figure 7 (*a*) shows a cluster of spheres produced when the metal abraded was pure cobalt. Here many small smooth spheres are evident, ranging in diameter from $\frac{1}{2}$ micron to several microns. Figure 7 (*b*) is a micrograph of a

particularly large cobalt sphere at higher magnification. This sphere is very regular, probably due to having been molten for sufficient time to allow surface tension to shape it. What appear to be grain boundaries outline grains that are unusually small (a few tenths of a micron in many cases) suggesting that the particle was cooled from the molten state at an extremely rapid rate.

Fig. 4

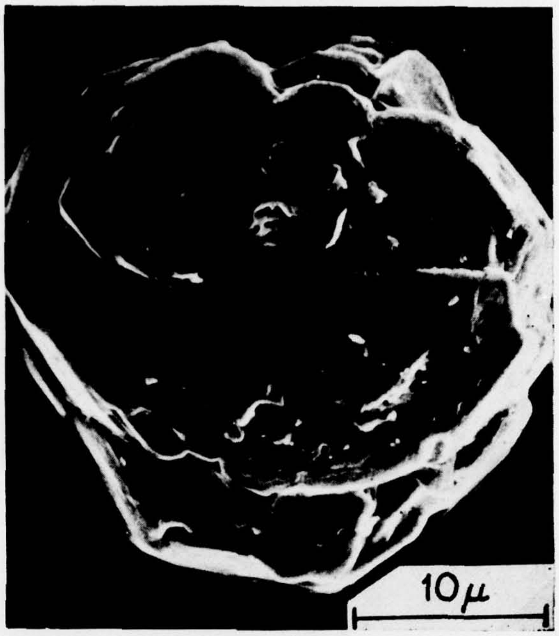


A platelet that has curled around a particle, to form a cocoon-like enclosure, similar to fig. 3, resulting in a more nearly spherical shape.

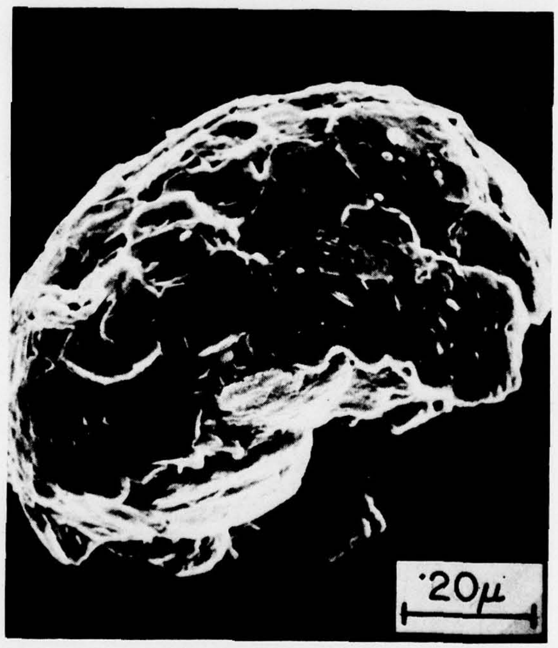
§ 3. Discussion

When new surfaces are generated under perfectly brittle conditions and moved far apart the energy required per unit area is termed surface energy. This energy is not converted to thermal energy as in the case of plastic processes but initially resides in the materials fractured as a super energy associated with a non-equilibrium surface structure. Such a structure can normally exist in a high vacuum at room temperature for a long time. The equilibrium surface structure has ions that are less closely spaced than those for the material in bulk and fewer negative charge carriers (free electrons in the case of a metal). The equilibrium state is normally attained only after the emission of a large number of electrons from the surface and a spreading of the surface ions. The emission of electrons from a freshly generated surface produced by cutting, scratching, denting or fracture is called the Kramer effect (Kramer 1950). Figure 8 shows the change in electron emission rate with time when aluminium is deeply scratched to produce new area.

Fig. 5

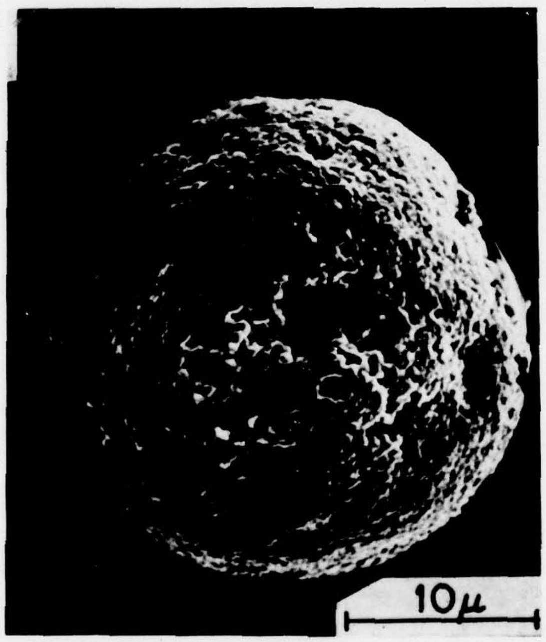


(a)



(b)

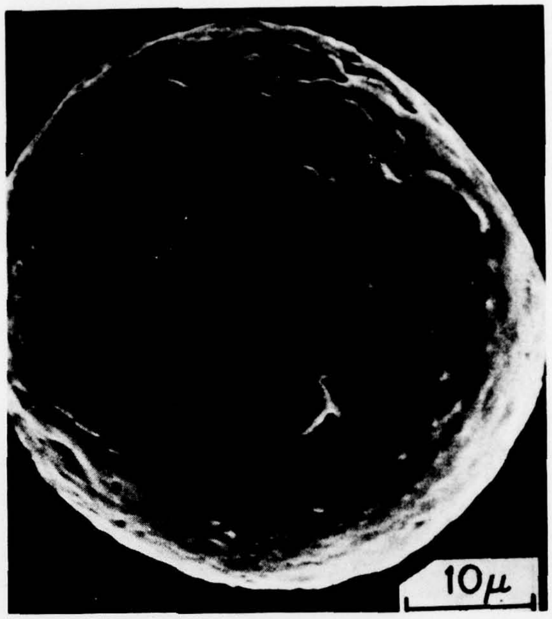
(*c*)



(*d*)

(*a*)–(*d*) Illustration of spherical particles formed from small individual platelets covering a small area of the sphere of which they became a part.

Fig. 6

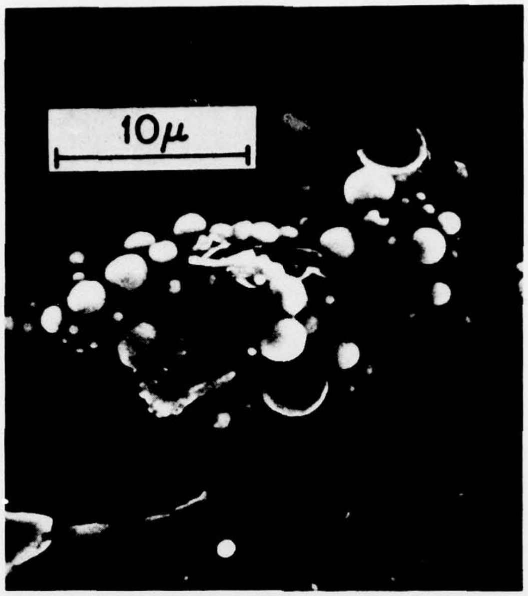


Smooth and rounded particle formed possibly by sintering and coalescence of several individual particles as a result of high temperature.

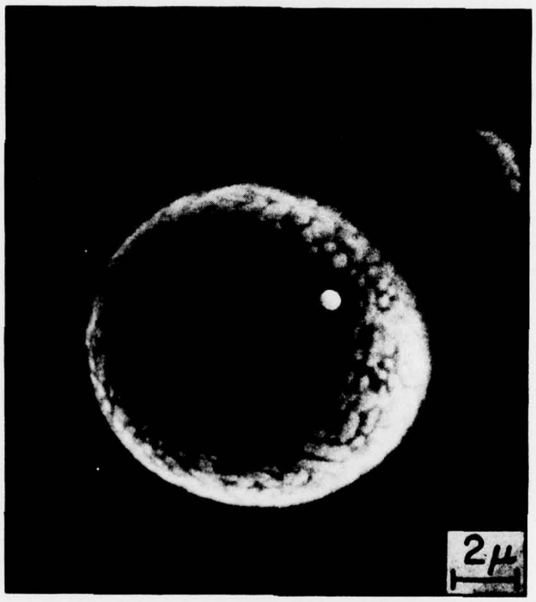
A valuable review of the Kramer effect has been presented by Grunberg (1958) from which it appears that the emission of electrons is accelerated by irradiation with X-rays, ultraviolet or even visible light. It is also evident that chemical action involving electron transfer such as oxidation promotes the attainment of equilibrium. It is now believed that mechanical activation (Shaw 1948) used to induce organometallic reactions involves the excess electrons in newly-generated surfaces as well as the high temperatures and pressures and cleanness of surface. The fact that it takes so long for equilibrium to be established in the case of fig. 8 is undoubtedly due to the fact that the associated surface oxidation is diffusion-controlled. It will be found on reading Grunberg (1958) that the mechanism of electron emission from a freshly-generated surface as equilibrium is established is not completely understood. However, this is not of great importance to the present study. The pertinent observation here is that a freshly-generated metal surface has more free electrons than required by the equilibrium spacing of ions in a free surface.

The particles removed in *fine* grinding are very thin platelets that are a micron or less in thickness. While the mechanism of chip formation in grinding is a somewhat controversial subject (see for example, Larsen-Basse and Oxley 1972, Komanduri 1971, Shaw 1972, and Doyle 1973), the fact remains that in *fine* grinding the material removed is in the form of thin platelets that tend to curl tightly into spheres or to form a layered structure.

Fig. 7



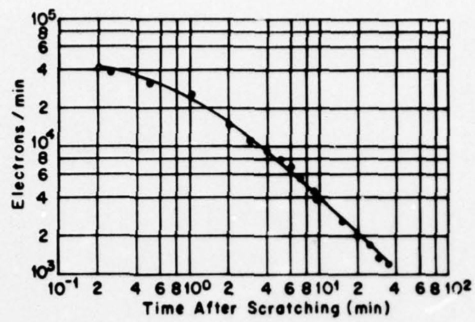
(*a*)



(*b*)

(*a*) Cluster of spheres produced when pure cobalt was abraded by silicon carbide at very high speed. (*b*) Micrograph of one of the cobalt spheres in fig. 7 (*a*) at higher magnification.

Fig. 8



Variation of rate of electron emission with time, after scratching an aluminium surface (Meyer 1967).

As already mentioned, the electron density of a freshly generated surface can be made consistent with its ion spacing by the loss of electrons from the surface (Kramer effect). An alternative way of achieving this, in the case of a very thin specimen, is for the specimen to curl with the newly generated surface on the concave side. This will force the ions in this surface to be more closely spaced and thus make it unnecessary for electrons to be emitted from the new surface. Figure 9 shows the situation that should exist for a thin freshly generated platelet. The upper (old) surface will be in equilibrium relative to electron density but the lower (new) surface will not be. The upper surface will be highly positive relative to the lower surface which will have an excess of electrons. The upper surface will be subjected to a surface tension (T) relative to the rest of the platelet and this will give rise to a constant bending moment $[(M_b = Tb(h)/(2))]$ along the length of the platelet.

Fig. 9

Freshly generated platelet with surface tension force acting on outer (old) surface only.

A linearly elastic beam that is subjected to pure bending (fig. 10) will assume a radius of curvature (ρ) given by the following equation (Crandall and Dahl 1959)

$$\frac{1}{\rho} = \frac{M_b}{EI_{yy}}, \tag{1}$$

where E is Young's modulus of elasticity and I_{yy} is the moment of inertia of the cross section of the beam about neutral axis yy.

For the beam of fig. 9

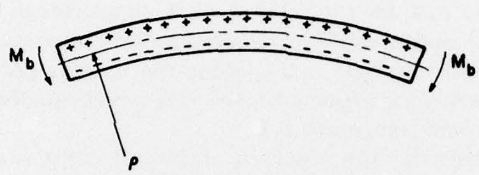
$$I_{yy} = \tfrac{1}{12} b h^3, \tag{2}$$

and hence

$$\rho = \frac{Ebh^3}{12Tb\dfrac{h}{2}} = \frac{Eh^2}{6T}. \tag{3}$$

For a platelet that is wide relative to its length (i.e. $l \gtrsim b$) ρ will be the radius of a sphere instead of a cylinder.

Fig. 10



Elastic beam subjected to pure bending.

Thus, a first consequence of the lower surface being out of equilibrium relative to electron density is a bending moment that will make a thin platelet curl in such a way that the old surface is outboard and the new surface is the concave side. A second consequence is that the curved platelet is highly polarized, being positively charged on its outer surface and negatively charged on its inner surface. As a result of this, curled platelets will be attracted to other platelets to form a layered structure.

This surface energy theory of spherical particle formation is in qualitative agreement with the complete range of morphologies shown in figs. 2 to 7. If the length of a platelet is large relative to its thickness it will tend to coil up and form a ball or a cylinder as in fig. 2. If, on the other hand, the length of a platelet is small relative to its thickness, it will merely tend to form a concave particle as in fig. 5. When such particles approach a sphere that has a positively charged outer surface their inner surfaces (negatively charged) will be attracted to the sphere. A strong bonding force will result that forces the curvature of the thin particle to conform to that of the sphere. Figures 5 represent examples of this type of action. If the temperature of the sphere is sufficiently high the individual platelets will merge into a single structure (fig. 6).

The radius of curvature that a particle assumes will depend largely on its thickness (h) and its temperature. At room temperature the value of ρ will be

relatively large. For example, for a platelet of steel having the following values

$$E = 21\,100 \text{ Kg/mm}^2 \ (30 \times 10^6 \text{ p.s.i.}),$$

$$h = 1 \text{ micron } (39{\cdot}4 \times 10^{-6} \text{ in.}),$$

$$T = 2000 \text{ ergs/cm}^2 \ (0{\cdot}0114 \text{ in lb/in.}^2),$$

it follows from eqn. (3) that

$$\rho = \frac{(21\,100)(10^{-6})(9{\cdot}807 \times 10^5)}{6(2000)} = 1{\cdot}72 \text{ cm } (0{\cdot}7 \text{ in.}).$$

As the temperature increases, both E and T will decrease, but E will decrease more rapidly than T, as the melting point is reached. In fact, at the melting point, E goes to zero while T assumes the value for liquid metal which will be the same as that for the solid at room temperature within a factor of two. Since in high-speed abrasive processing the temperature of an extruded platelet will be relatively high, approaching the melting point, the value of ρ for a given thickness (h) is expected to be very much smaller than the corresponding value at room temperature.

Other mechanisms for the observed curling of chips that have been considered include that due to possible differential thermal expansion and a differential degree of oxide formation on the old and new surfaces. The difference in length of an old and new surface will equal $\alpha l \Delta\theta$ where α is the coefficient of linear expansion, l is the length of the chip and $\Delta\theta$ is the difference in temperature between the two surfaces. The order of magnitude of α and l will each be 10^{-6} while $\Delta\theta$ will be much less than 10^4. This results in the change of length of the two surfaces being of the order of 10^{-8} and hence will result in negligible curvature. Alternatively, if one surface is more highly oxidized than the other this will give rise to a difference in surface forces resulting in a bending moment that is negligible compared with that involved in the non-equilibrium theory previously presented.

The spherical chips shown in figs. 2 to 7 do not appear to have oxidized. This is an unexpected result since most small chips react rapidly in air and become visible, incandescent and finally explode into patterns of sparks characteristic of the metal being ground. A possible explanation for the non-pyrophoric behaviour of the chips shown here is that they have assumed equilibrium between ion-spacing and electron density by bending rather than by emission of electrons. Ordinary grinding chips are thicker than those shown here and therefore do not curl. The excess electrons in the new surface are then available to promote reaction with air and since this reaction is highly exothermic further reaction is accelerated until the particles explode like a meteorite entering the earth's atmosphere.

The mechanism of spherical chip formation described here for fine grinding is also believed to hold under conditions of accelerated wear. The wear particles under such conditions are frequently observed to be platelets. These platelets should be highly charged and if generated at a sufficiently high

temperature, should have a tendency to curl. The presence of platelets with oppositely charged surfaces should play an important role in the multiple transfer aspect of most systems that wear. The old (positively charged) surface of a freshly generated particle from one sliding element will be attracted and bonded to a newly generated (negatively charged) surface on the second sliding element. In this way platelets should tend to transfer back and forth from one surface to another. While this aspect of wear is normally disadvantageous because it leads to a roughening of the interface (galling) and an increase in friction it is highly important in the process known as friction- or inertia-welding. In this case multiple transfer is very desirable when joining dissimilar metals since it provides a joint of gradually changing properties rather than a sharp interface. The unusual strength of friction-welded joints involving dissimilar metals is believed to be due largely to the high degree of mixing at the interface that results from multiple transfer. The development of wear platelets whose surfaces are oppositely charged should therefore play an important role in friction welding.

§ 4. Conclusions

(1) Spherical chips having a wide range of morphologies are formed from platelets generated in very fine grinding.

(2) A theory of spherical chip formation based upon the assumption that it takes a freshly generated surface on a thin specimen a relatively short time to assume its equilibrium ion spacing and negative charge density by curling, but a relatively long time by loss of electrons through a diffusion-controlled oxidation reaction, is in good qualitative agreement with the range of spherical chip morphologies observed in the scanning electron microscope.

(3) The small chips that have formed into spheres appear to be relatively free of oxidation. This unexpected result is probably due to the fact that the platelets generated achieve equilibrium relative to electron density by curling rather than by electron emission.

(4) The conditions leading to spherical chip formation should be pertinent relative to accelerated wear leading to galling and to friction welding.

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